

Fuzzy Multiattribute Evaluation of Airport Performance

Chung-Hsing Yeh and Yu-Liang Kuo

Faculty of Information Technology
Monash University

Clayton, Victoria 3800, Australia

E-mail: ChungHsing.Yeh@infotech.monash.edu.au

Yu-Hern Chang

Department of Transportation and Communications
Management

National Cheng Kung University, Tainan, Taiwan

E-mail: yhchang@mail.ncku.edu.tw

Abstract— This paper presents a fuzzy multiattribute decision making (MADM) approach to evaluating airport performance in terms of the airport operator, the passenger, and the airline dimensions. Assessments for quantitative measures are represented by crisp values, and assessments for qualitative measures and attribute weights are represented by triangular fuzzy numbers, obtained via surveys using linguistic terms. An effective algorithm is developed by using the α -cut concept for incorporating the decision-maker's confidence level about respondents' fuzzy assessments on performance ratings and attribute weights. Based on the concept of the degree of optimality, the algorithm obtains a quantitative performance index for each airport evaluated, relative to other comparable airports with respect to each of three evaluation dimensions individually and all three evaluation dimensions as a whole. The performance index obtained would help individual airports understand the comparative level of their performance on measures relating to operational management, airport facilities, and passenger service quality. An empirical study of performance evaluation of 11 Asia-Pacific major international airports is conducted to illustrate how the approach works.

Keywords—Fuzzy multiattribute decision making; Airport performance evaluation; TOPSIS

I. INTRODUCTION

The operation efficiency and service quality of international airports are critical in the modern-day context where businesses are international and people are more mobile. To help an airport identify functional areas for improvement, it is advisable to evaluate its performance relative to other comparable airports with respect to a number of manageable attributes (evaluation criteria). As the evaluation is based on a comparative process, the evaluation result can be used as a service benchmarking and management tool for airports. The most comprehensive study of comparing service performance of international airports is probably the International Air Transport Association (IATA) Global Airport Monitor. Despite a wide coverage of performance indicators for airport services, no attempt was made by IATA to develop an integrated airport performance index.

Quite a few studies on airport performance evaluation have been reported in the literature with focus on specific functional areas of airport operations, such as productivity [1]–[4],

capacity and delays [5], efficiency [6]–[8], airline services [9], competitiveness [10], [11], financial performance [12], service quality [13]–[15]. Although there is no universal and exact definition for airport performance, the overall performance of airports can be measured from the viewpoints of passengers, airlines, and the airport operator [16]. The most widely used airport performance evaluation methods are perhaps the data envelopment analysis (DEA) and total factor productivity (TFP) [3], [6]–[8], [17], [18]. Although these methods are well suited for measuring the efficiency of airport operations based on resource input measures and performance output measures, they do not intend to address the effectiveness issue with respect to the overall performance of airports from the viewpoints of the airport operator, passengers, and airlines as a whole.

The evaluation of the overall performance of airports is a complex decision-making process, as it usually involves (a) multiple conflicting criteria with non-commensurable units and (b) both crisp and fuzzy data derived from precise measures of quantitative criteria and imprecise judgments of qualitative criteria resulting from human subjectivity. Multiattribute decision making (MADM) has proven to be an effective approach for ranking a finite number of alternatives characterized by multiple conflicting criteria [19]. The most widely used theory in solving MADM problems is multiattribute utility theory [20] or multiattribute value theory (MAVT) [21], with which a cardinal preference or ranking of the decision alternatives is generated. Fuzzy set theory has proven to be a powerful modeling tool for coping with the subjectiveness and imprecision of human judgments [22], [23]. In the applications of MAVT-based MADM for evaluation and selection problems involving subjective judgments of the decision maker, fuzzy MADM has demonstrated its applicability in ranking decision alternatives such as transportation systems (e.g. [10], [24]–[28]).

In this paper, we formulate the evaluation of airport performance as a fuzzy MADM problem that requires cardinal ranking. To obtain a quantitative airport performance index, we develop an algorithm based on the concept of the degree of optimality. In subsequent sections, we first discuss the performance measures suitable for evaluating the airport performance from the perspectives of the airport operator, passengers, and airlines. We then present the fuzzy MADM

approach to the performance evaluation problem. Finally we conduct an empirical study to measure and compare the overall performance of 11 major Asia-Pacific international airports.

II. AIRPORT PERFORMANCE MEASURES

The use of performance measures (attributes) in airport evaluation problem is crucially important because of its specific economic characteristics. In the business competitive environment optimal performance can be equated with profitability. However, the conditions under which airports operate are far from competitive. Regulatory, geographical, economic, social and political constraints all hinder direct competition between airports [29]. Various performance attributes or measures can be used to evaluate the airport performance from the perspectives of different stakeholders of the airport operation, depending on the objectives of the evaluation problem. In the case of airport performance evaluation, the airport operator (service provider) would focus more on measures concerned with the operational efficiency of the airport. Passengers are more interested in measures relating to service quality and safety. Airlines are more concerned about the facilities provided by the airport. As such, to reflect the operating characteristics of international airports, the criteria for performance evaluation should be constructed from the perspectives of the airport operator, passengers, and airlines. Fig. 1 shows the hierarchical structure of the airport evaluation problem to be addressed in the paper. The three evaluation dimensions and their associated performance measures are discussed below.

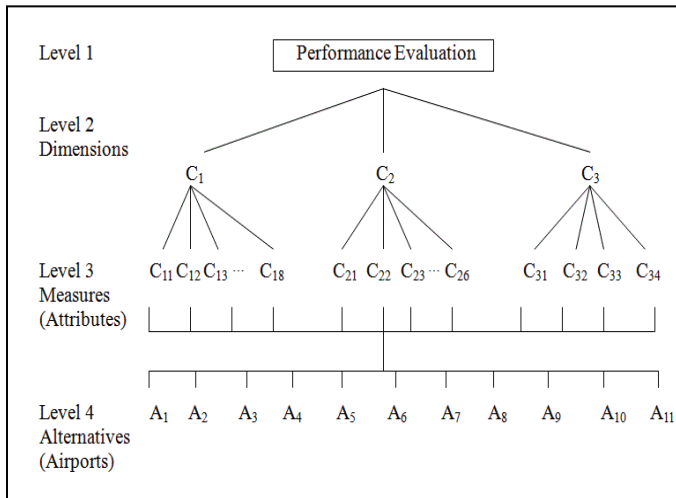


Figure 1. Hierarchy structure for airport performance evaluation.

The airport operator dimension (C_1) is mainly concerned with airport operational management and the facilities provided for the airport users. The airport operator is assessed quantitatively based on the airport operational data, including revenue (C_{11}) (total operating revenue), annual growth rate (C_{12}) (annual growth rate of total passenger volume), airport terminal size (C_{13}) (total terminal surface area of airport), navigation Aids (C_{14}) (category of the navigation aid system),

ground access facilities (C_{15}) (types of ground transportation to/from city), distance to CBD (C_{16}) (distance from the airport to the central business district), car park (C_{17}) (number of parking car bays), noise pollution (C_{18}) (number of aircraft movement per day).

The passenger dimension (C_2) relates to the services provided by the airport and the quality level as perceived by the passengers. These service measures include comfort (C_{21}) (congestion level and cleanliness in the terminal building), processing time (C_{22}) (total time required during check-in, immigration inspection and customs), convenience (C_{23}) (availability and accessibility of airport facilities within the terminal building), courtesy of staff (C_{24}) (helpfulness and friendliness of airport staff), information visibility (C_{25}) (information display for flights, airport facilities, and signposting), security (C_{26}) (safety measures and security facilities). These service attributes are to be measured based on passengers' perception, which are to be assessed subjectively by a survey process using a set of linguistic terms characterized by fuzzy numbers.

The airline dimension (C_3) is mainly concerned with the facilities provided by airports such as gates, operating hours, aircraft movement and runways. Its performance measures include aircraft movement (C_{31}) (total number of aircraft movement), gates (C_{32}) (number of gates), operating hours (C_{33}) (total daily operating hours of the airport), runway (C_{34}) (number of runways).

The performance measures discussed above involve both quantitative and qualitative assessments, for which numerical data and fuzzy numbers are to be used respectively. These measures are independent of each other, thus suitable for use in an MAVT-based MADM model.

III. THE FUZZY MULTIATTRIBUTE DECISION MAKING APPROACH

A. The Evaluation Problem

In this paper, we formulate the airport performance evaluation as a fuzzy MADM problem that requires cardinal ranking. The problem involves a set of m airports (alternatives) A_i ($i = 1, 2, \dots, m$), which are to be evaluated based on n evaluation dimensions C_j ($j = 1, 2, \dots, n$), each of which is represented by a set of p_j performance measures (attributes) C_{jk} ($k = 1, 2, \dots, p_j$). Assessments are to be given to determine (a) the weight vectors $W = (w_1, w_2, \dots, w_j, \dots, w_n)$ and $W_j = (w_{j1}, w_{j2}, \dots, w_{jk}, \dots, w_{jp_j})$ ($j = 1, 2, \dots, n; k = 1, 2, \dots, p_j$), and (b) the decision matrices $Y_{C_j} = \{y_{ki}, k = 1, 2, \dots, p_j; i = 1, 2, \dots, m\}$ ($j = 1, 2, \dots, n$) and $X = \{x_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\}$.

The weight vectors W and W_j represent the relative importance of n evaluation dimensions C_j ($j = 1, 2, \dots, n$) and p_j performance measures C_{jk} ($k = 1, 2, \dots, p_j$) for the problem and their corresponding dimension respectively. The weight vectors are to be assessed subjectively by airport experts via surveys, using the set of linguistic terms defined in Table I. Linguistic terms have been found intuitively easy to use in

expressing the subjectiveness and imprecision of the decision maker's assessments [23], [30]–[32]. To facilitate the making of qualitative assessments by respondents, a set of linguistic terms is used. Each linguistic term is characterized by a triangular fuzzy number for representing its approximate value range between 1 and 9, denoted as (a_1, a_2, a_3) , where $1 \leq a_1 \leq a_2 \leq a_3 \leq 9$. a_2 is the most possible value of the term, and a_1 and a_3 are the lower and upper bounds respectively used to reflect the fuzziness of the term. As such, w_j in W and w_{jk} in W_j are the fuzzy weights of evaluation dimensions C_j ($j = 1, 2, \dots, m$) and performance measures C_{jk} ($k = 1, 2, \dots, p_j$), respectively.

TABLE I. LINGUISTIC TERMS USED FOR DETERMINING THE WEIGHT VECTOR

Linguistic Term	Not Important (NI)	Somewhat Important (SI)	Important (I)	Very Important (VI)	Extremely Important (EI)
Membership Function	(1,1,3)	(1,3,5)	(3,5,7)	(5,7,9)	(7,9,9)

In practical applications, the triangular form of the membership function is used most often for representing fuzzy numbers that characterize linguistic information [33], [34]. The popular use of triangular fuzzy numbers is mainly attributed to their simplicity in both concept and computation. Theoretically, the merits of using triangular fuzzy numbers in fuzzy modeling have been well justified [35]. With the simplest form of the membership function, triangular fuzzy numbers constitute an immediate solution to the optimization problems in fuzzy modeling.

The decision matrices Y_{C_j} represent the performance ratings (y_{ki}) of airport A_i with respect to each performance measure C_{jk} ($k = 1, 2, \dots, p_j$) of the corresponding evaluation dimension C_j . These performance ratings are given based on quantitative and qualitative assessments. While the quantitative assessments are straightforward based on the data available, the qualitative assessments require subjective judgments of airport experts to reflect the degree to which each airport satisfies each qualitative safety measure. The set of linguistic terms defend in Table II is used by airport experts to assess the qualitative performance ratings via surveys.

TABLE II. LINGUISTIC TERMS USED FOR DETERMINING PERFORMANCE RATINGS

Linguistic Term	Very Poor (VP)	Poor (P)	Fair (F)	Good (G)	Very Good (VG)
Membership Function	(1,1,3)	(1,3,5)	(3,5,7)	(5,7,9)	(7,9,9)

The decision matrix $X = \{x_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\}$ represents the performance ratings of airport A_i with respect to evaluation dimension C_j . While Y_{C_j} ($j = 1, 2, \dots, n$) are given based on the assessments made on the airports, the decision matrix X is constructed by aggregating the weighted assessments from lower-level performance measures of each evaluation dimension C_j . Given the fuzzy weight vectors (W

and W_j) and fuzzy decision matrices (X and Y_{C_j}), the objective of the problem is to rank all the airports by giving each of them an overall airport performance index with respect to all evaluation dimensions.

B. The Solution Procedure

The algorithm begins with the generation of the decision matrix X by multiplying the weight vector W_j by the decision matrix Y_{C_j} , as

$$(x_{1j}, x_{2j}, \dots, x_{mj}) = W_j Y_{C_j} / \sum_{k=1}^{p_j} w_{jk}, j = 1, 2, \dots, n. \quad (1)$$

where Y_{C_j} ($i = 1, 2, \dots, m$) are the normalized decision matrices by

$$y_{ki} = y_{ki} / \sqrt{\sum_{i=1}^n (y_{ki})^2}, i = 1, 2, \dots, m; k = 1, 2, \dots, p_j. \quad (2)$$

The normalization process is required to allow a comparable scale for all performance measures, assessed by different measurement units.

In (1), $(x_{1j}, x_{2j}, \dots, x_{mj})$ is a fuzzy decision vector in X , which is obtained from a normalized value function that multiplies the weight vector W_j for its lower-level sub-criteria C_{jk} by the corresponding normalized decision matrix Y_{C_j} . With the use of triangular fuzzy numbers, the arithmetic operations on fuzzy numbers are based on interval arithmetic [36].

The algorithm then generates a fuzzy performance matrix by multiplying the weight vector W by the decision matrix X , as given in (3).

$$Z = \begin{bmatrix} w_1 x_{11} & w_2 x_{12} & \dots & w_n x_{1n} \\ w_1 x_{21} & w_2 x_{22} & \dots & w_n x_{2n} \\ \dots & \dots & \dots & \dots \\ w_1 x_{m1} & w_2 x_{m2} & \dots & w_n x_{mn} \end{bmatrix} \quad (3)$$

By using the concept of α -cut on the fuzzy numbers in the performance matrix, an interval performance matrix is derived as given in (4), where $0 \leq \alpha \leq 1$. For a given α , z_{ijl}^α and z_{ijr}^α ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$) are the average of the lower bounds and upper bounds of the crisp intervals respectively, resulted from all α -cuts using the alpha values equal to or greater than the specified value of α .

$$Z_\alpha = \begin{bmatrix} [z_{11l}^\alpha, z_{11r}^\alpha] & [z_{12l}^\alpha, z_{12r}^\alpha] & \dots & [z_{1nl}^\alpha, z_{1nr}^\alpha] \\ [z_{21l}^\alpha, z_{21r}^\alpha] & [z_{22l}^\alpha, z_{22r}^\alpha] & \dots & [z_{2nl}^\alpha, z_{2nr}^\alpha] \\ \dots & \dots & \dots & \dots \\ [z_{m1l}^\alpha, z_{m1r}^\alpha] & [z_{m2l}^\alpha, z_{m2r}^\alpha] & \dots & [z_{mnl}^\alpha, z_{mnr}^\alpha] \end{bmatrix} \quad (4)$$

The value of α represents the decision maker's degree of confidence in the fuzzy assessments, given by the respondents with respect to attribute weights and performance ratings of airports. A larger α value indicates that the decision maker is

more confident in choosing a crisp value interval to represent the corresponding fuzzy number, as the interval is smaller and has a higher possibility. This implies that a confident decision maker would not consider less possible values embedded in a fuzzy number.

To reflect the decision maker's relative preference between z_{ijl}^{α} and z_{ijr}^{α} in (4), a preference index λ in the range of 0 and 1 is incorporated in the algorithm. As a result, a crisp performance matrix is obtained as

$$Z_{\alpha}^{\lambda} = \begin{bmatrix} z_{11\alpha}^{\lambda'} & z_{12\alpha}^{\lambda'} & \cdots & z_{1m\alpha}^{\lambda'} \\ z_{21\alpha}^{\lambda'} & z_{22\alpha}^{\lambda'} & \cdots & z_{2m\alpha}^{\lambda'} \\ \cdots & \cdots & \cdots & \cdots \\ z_{n1\alpha}^{\lambda'} & z_{n2\alpha}^{\lambda'} & \cdots & z_{nm\alpha}^{\lambda'} \end{bmatrix} \quad (5)$$

where $z_{ij\alpha}^{\lambda'} = \lambda z_{ijr}^{\alpha} + (1-\lambda)z_{ijl}^{\alpha}$, $0 \leq \lambda \leq 1$, $i = 1, 2, \dots, m$; $j = 1, 2, \dots, n$. The use of λ allows the algorithm to reflect the decision maker's attitude towards risk, which may be optimistic, pessimistic or somewhere in between. In actual decision settings, $\lambda = 1$, $\lambda = 0.5$, or $\lambda = 0$ can be used to indicate that the decision maker has an optimistic, moderate, or pessimistic view respectively on fuzzy assessment results. An optimistic decision maker is apt to prefer higher values of the crisp value interval derived from fuzzy assessments, while a pessimistic decision maker tends to favor lower values.

To solve the multiattribute evaluation problem characterized by the perform matrix in (5), an effective method is applied. The method is based on the concept of the degree of optimality rooted in an alternative where multiple attributes (criteria) characterize the notion of the best [37]. In the context of MADM, the concept suggests that the most preferred alternative should not only have the shortest distance from the positive ideal solution (or the best alternative), but also have the longest distance from the negative ideal solution (or the worst alternative). The positive (or negative) ideal solution consists of the best (or worst) attribute values attainable from all the alternatives if each attribute takes monotonically increasing or decreasing values [19]. This concept has been implemented by a widely used MADM method called the technique for order preference by similarity to ideal solution (TOPSIS) [19] and has been applied under different decision contexts [38]–[44]. This is mainly due to (a) its applicability in solving various practical decision problems, (b) its simplicity and comprehensibility, (c) its computational efficiency, and (d) its ability to measure the relative performance of the alternatives in a simple mathematical form.

Based on the concept presented above, the positive ideal solution $A_{\alpha}^{\lambda+}$ and the negative ideal solution $A_{\alpha}^{\lambda-}$ can be determined from (5) by selecting the maximum value and the minimum value respectively across all alternatives (airports) with respect to each service attribute, as given in (6) and (7).

$$\begin{aligned} A_{\alpha}^{\lambda+} &= (z_{1\alpha}^{\lambda+}, z_{2\alpha}^{\lambda+}, \dots, z_{n\alpha}^{\lambda+}) \\ A_{\alpha}^{\lambda-} &= (z_{1\alpha}^{\lambda-}, z_{2\alpha}^{\lambda-}, \dots, z_{n\alpha}^{\lambda-}) \end{aligned} \quad (6)$$

where

$$\begin{aligned} z_{j\alpha}^{\lambda+} &= \max(z_{1j\alpha}^{\lambda}, z_{2j\alpha}^{\lambda}, \dots, z_{mj\alpha}^{\lambda}) \\ z_{j\alpha}^{\lambda-} &= \min(z_{1j\alpha}^{\lambda}, z_{2j\alpha}^{\lambda}, \dots, z_{mj\alpha}^{\lambda}) \end{aligned}, j = 1, 2, \dots, n \quad (7)$$

$A_{\alpha}^{\lambda+}$ and $A_{\alpha}^{\lambda-}$ represent the performance vectors of the best possible airport and the worst possible airport on n service attributes respectively.

Like the performance vectors in (6), the weighted overall performance of airport A_i on service attributes C_j ($j=1, 2, \dots, n$) can be expressed as a performance vector of n elements. Thus, we can apply the vector matching technique to measure how close a particular airport is to the best possible airport and to the worst possible airport, given respectively as

$$S_{i\alpha}^{\lambda+} = \frac{A_{i\alpha}^{\lambda} A_{\alpha}^{\lambda+}}{\max(A_{i\alpha}^{\lambda} A_{i\alpha}^{\lambda}, A_{\alpha}^{\lambda+} A_{\alpha}^{\lambda+})} \quad (8)$$

$$S_{i\alpha}^{\lambda-} = \frac{A_{i\alpha}^{\lambda} A_{\alpha}^{\lambda-}}{\max(A_{i\alpha}^{\lambda} A_{i\alpha}^{\lambda}, A_{\alpha}^{\lambda-} A_{\alpha}^{\lambda-})}, i=1, 2, \dots, m \quad (9)$$

$A_{i\alpha}^{\lambda}$ is the i^{th} row of the performance matrix in (5), representing the corresponding performance vector of airport A_i with respect to service attribute C_j . $S_{i\alpha}^{\lambda+}$ and $S_{i\alpha}^{\lambda-}$ represent the degree of similarity between airport A_i and the positive ideal solution and the negative ideal solution respectively.

For a given decision maker's degree of confidence level (α) in fuzzy assessments and a given index of optimism (λ), an overall performance index for each airport can be determined by

$$P_{\alpha i}^{\lambda} = \frac{S_{i\alpha}^{\lambda+}}{S_{i\alpha}^{\lambda+} + S_{i\alpha}^{\lambda-}}, i=1, 2, \dots, m. \quad (10)$$

The rationale behind (10) is that that a preferred alternative should have a higher degree of similarity to the positive ideal solution and a lower degree of similarity to the negative ideal solution [19]. The larger the performance index, the better the overall service performance of the airport, relative to other airports. As such, the performance index generated is a relative concept, and indicates the relative ranking of the airports evaluated in terms of service attributes.

IV. EMPIRICAL STUDY OF 11 ASIA-PACIFIC INTERNATIONAL AIRPORTS

To illustrate how the fuzzy MADM approach works, we conducted an empirical study on 11 major international airports in the Asia-Pacific region. Air travel demand in the Asia-Pacific region had an average annual growth rate of 10.1% during the past decade, the highest in the world. A high rate of economic growth in Asia has spurred the rapid expansion of commercial aviation industries serving the Asia-Pacific region. With 16 of the world's 25 busiest air routes, Asia's major airports are already near capacity. Asia's explosive economic growth has been accompanied by rapid expansion and the transformation of the region's aviation industry. Air transportation is expected to play a larger role in this region more than anywhere else in the world. First, the high

population and income growth rates in many Asian countries are expected to produce an astounding increase in the demand for air transportation services. The region already accounts for more than 50 per cent of the world's population. Second, vast distances separate many Asia-Pacific countries. About 60 per cent of the air routes in the region are between cities that are at least 2,000 kilometers apart, and a number of countries in the region are islands or archipelagos with few alternatives to air passenger travel [45].

The purpose of this study is to evaluate the performance of Asia-Pacific's 11 major international airports on measures relating to operational management, passenger service quality, and airport facilities. The 11 major airports selected process more than half of the region's international traffic. These airports are (A_1) Incheon International Airport - Incheon (ICN), (A_2) Chek Lap Kok International Airport - Hong Kong (HKG), (A_3) Suvarnabhumi International Airport - Bangkok (BKK), (A_4) Narita International Airport - Tokyo (NRT), (A_5) Changi International Airport - Singapore (SIN), (A_6) Kingsford Smith International Airport - Sydney (SYD), (A_7) Kansai International Airport - Osaka (KIX), (A_8) Capital International Airport - Beijing (PEK), (A_9) Taoyuan International Airport - Taipei (TPE), (A_{10}) Tullamarine International Airport - Melbourne (MEL) and (A_{11}) Pudong International Airport - Shanghai (PVG). The performance of these 11 airports is to be evaluated based on the three dimensions and their associated performance measures as shown in Fig. 1.

In this study, we use equal weights for the three evaluation dimensions, i.e. $W = (1, 1, 1)$. The weights of performance measures within each dimension are assessed by airport experts using the linguistic terms defined in Table I. Table III shows the assessment result.

TABLE III. WEIGHT VECTOR FOR EVALUATION DIMENSIONS

Weight Vector	Fuzzy Weights for Performance Measures
W	(1, 1, 1)
W_1 (Airport operator)	(VI, EI, VI, I, I, I, VI, I)
W_2 (Passenger)	(VI, VI, VI, EI, I, VI)
W_3 (Airline)	(I, VI, VI, I)

The assessment results of the performance measures for the airport operator and the airline dimensions are obtained from the available data for 2008 as crisp data, as given in Tables IV and V respectively. The assessment for qualitative performance measures of the passenger dimension is made by surveys of 15 international tour guides using the linguistic terms defined in Table II. Table VI shows the assessment result.

With the data in Tables III - VI, the decision matrix for the three evaluation dimensions can be calculated by (1). The fuzzy performance matrix in (3) can then be obtained by multiplying this decision matrix by the weight vector W of equal weights. By applying the algorithm given as in (4)-(10) with $\alpha = 0$ and $\lambda = 0.5$, we can obtain an airport performance

index for each airport with respect to each evaluation dimension individually and all the three dimensions as a whole. Table VII shows the result and the corresponding ranking order.

TABLE IV. ASSESSMENT DATA FOR THE AIRPORT OPERATOR DIMENSION

Airport	Revenue 000,000 ' (C_{11})	Annual Growth Rate % (C_{12})	Airport Terminal Size '000 m ² (C_{13})	Naviga- tion Aids (C_{14})	Ground Access (C_{15})	Distance to CBD km (C_{16})	Car Park (C_{17})	Noise Pollution (C_{18})
A ₁	973	-4	600	2	3	52	11,303	578
A ₂	1,120	1.7	710	3	2	40	4,010	811
A ₃	206	-6.3	283	3	2	25	5,000	208
A ₄	1,830	-5.6	789	2	2	65	9,144	530
A ₅	921	2.7	1,043	2	2	20	5,420	614
A ₆	773	3	387	2	2	8	11,500	819
A ₇	959	-2.5	330	2	3	50	6,133	366
A ₈	561	4.4	1,382	2	2	26	7,000	1,177
A ₉	346	-4	487	2	1	40	6,441	367
A ₁₀	370	7.9	127	3	1	24	6,700	530
A ₁₁	482	-2.4	824	1	3	30	3,000	728

TABLE V. ASSESSMENT DATA FOR THE AIRLINE DIMENSION

Airport	Aircraft Movements (C_{31})	Gates (C_{32})	Operating Hours (C_{33})	Runway (C_{34})
A ₁	211,102	90	24	3
A ₂	296,000	106	24	2
A ₃	267,480	51	24	2
A ₄	193,321	87	17	3
A ₅	231,900	102	24	2
A ₆	298,964	65	17	3
A ₇	133,502	52	24	2
A ₈	429,646	120	24	3
A ₉	134,072	55	24	2
A ₁₀	193,500	62	24	2
A ₁₁	265,735	98	24	3

TABLE VI. ASSESSMENT DATA FOR THE PASSENGER DIMENSION

Airport	Comfort (C_{21})	Processing Time (C_{22})	Conve- nience (C_{23})	Courtesy of Staff (C_{24})	Information Visibility (C_{25})	Security (C_{26})
A ₁	G	G	F	F	F	G
A ₂	G	G	G	G	G	G
A ₃	F	F	F	F	F	F
A ₄	G	F	F	G	G	G
A ₅	VG	G	G	G	G	G
A ₆	F	F	F	F	F	F
A ₇	G	G	F	G	F	G
A ₈	F	F	F	F	F	F
A ₉	F	G	F	F	F	F
A ₁₀	F	F	F	F	F	G

A ₁₁	F	F	F	F	F	F
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TABLE VII. AIRPORT PERFORMANCE INDEX AND RANKING OF 11 AIRPORTS

Airport	Overall		C ₁		C ₂		C ₃	
	Index	Ranking	Index	Ranking	Index	Ranking	Index	Ranking
A ₁ (Incheon)	1.414	7	0.369	8	0.512	4	0.533	4
A ₂ (Hong Kong)	1.595	4	0.470	5	0.557	2	0.568	3
A ₃ (Bangkok)	1.392	8	0.445	6	0.481	7	0.465	8
A ₄ (Tokyo)	1.446	6	0.431	7	0.525	3	0.490	7
A ₅ (Singapore)	1.681	2	0.587	2	0.570	1	0.524	5
A ₆ (Sydney)	1.527	5	0.566	3	0.439	11	0.522	6
A ₇ (Osaka)	1.235	10	0.354	9	0.506	5	0.374	11
A ₈ (Beijing)	1.695	1	0.552	4	0.463	10	0.680	1
A ₉ (Taipei)	1.122	11	0.257	11	0.485	6	0.379	10
A ₁₀ (Melbourne)	1.671	3	0.763	1	0.480	8	0.428	9
A ₁₁ (Shanghai)	1.367	9	0.329	10	0.465	9	0.572	2

The settings used for α and λ reflect that the decision maker has no particular preference for the fuzzy assessment results made by the respondents. $\alpha = 0$ implies that the mean value of a fuzzy number; that is, the average of value intervals of all α -cuts on the fuzzy number is used. $\lambda = 0.5$ indicates that the decision maker has a moderate attitude towards the respondents' assessments; that is, the decision maker weights all the values derived from fuzzy assessments equally.

In terms of the overall performance, the Beijing, Singapore, and Melbourne airports perform best, while the Taipei, Osaka and Shanghai airports have the worst performance. On the airport operator dimension, the Melbourne airport ranks first with a good performance in all measures, while the Taipei airport ranks last, mainly because of its poor performance in the areas of revenue, annual growth rate, and ground access. The Melbourne airport performs exceptionally well on this dimension as compared with its performance on other dimensions, mainly due to its highest annual growth rate among all the airports. On the passenger dimension, the Singapore, Hong Kong, and Tokyo airports perform exceptionally well based on passengers' perception of airport service quality, while the Sydney, Beijing and Shanghai airports provide relatively poor passenger service quality. On the airline dimension, the Beijing, Shanghai and Hong Kong airports have the best performance, while the Osaka and Taipei airports perform worst.

To examine whether the confidence level (the α value) and the risk attitude (the λ value) may affect the evaluation result presented in Table VII, a sensitivity analysis process was carried out by changing the values of α and λ . Table VIII shows three representative evaluation results under three typical settings of λ regardless of the settings of α . Fig. 2 shows some representative evaluation results under various settings of α and λ . As shown in Table VIII and Fig. 2, when

the risk attitude is pessimistic or moderate ($\lambda = 0$ or $\lambda = 0.5$), the ranking result is not consistent. This implies that the decision maker's attitude towards the handling of the uncertainty associated with the fuzzy assessments in this case study does have significant influence on the evaluation result in terms of relative ranking. This is mainly due to the fact that these airports have relatively similar performances on the passenger service quality dimension than the other two dimensions. No airport appears to have a dominating performance in all three evaluation dimensions.

TABLE VIII. OVERALL AIRPORT PERFORMANCE INDEX AND RANKING UNDER VARIOUS RISK ATTITUDES

Airport	$\lambda = 0$		$\lambda = 0.5$		$\lambda = 1$	
	Index	Ranking	Index	Ranking	Index	Ranking
A ₁ (Incheon)	1.439	7	1.414	7	1.395	8
A ₂ (Hong Kong)	1.679	3	1.595	4	1.558	4
A ₃ (Bangkok)	1.119	10	1.392	8	1.478	6
A ₄ (Tokyo)	1.496	5	1.446	6	1.419	7
A ₅ (Singapore)	1.777	1	1.681	2	1.636	3
A ₆ (Sydney)	1.485	6	1.527	5	1.527	5
A ₇ (Osaka)	1.235	9	1.235	10	1.223	10
A ₈ (Beijing)	1.703	2	1.695	1	1.677	1
A ₉ (Taipei)	1.104	11	1.122	11	1.119	11
A ₁₀ (Melbourne)	1.656	4	1.671	3	1.667	2
A ₁₁ (Shanghai)	1.345	8	1.367	9	1.363	9

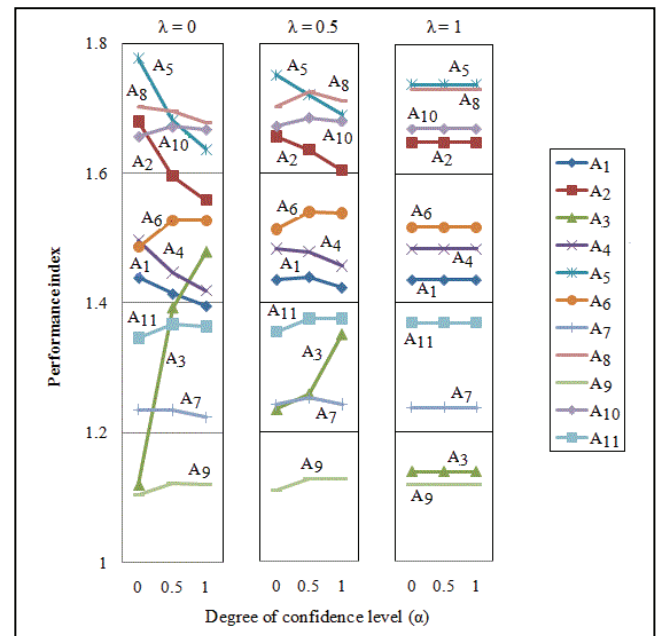


Figure 2. Overall airport performance index and ranking under various decision settings.

The performance index obtained would help airports understand the comparative level of their performance on

measures relating to operational management, airport facilities, and passenger service quality. With its relative concept, the index serves as a performance benchmarking and management tool for airports, as it can identify functional areas for performance improvement.

V. CONCLUSION

Airport performance evaluation requires considering multiple evaluation criteria structured in multi-level hierarchies. The evaluation often involves both quantitative and qualitative assessment data. In this paper, we have formulated airport performance evaluation as a fuzzy MADM problem that requires cardinal ranking of all airports. As an effective alternative to airport performance evaluation, the fuzzy MADM approach developed can effectively handle both quantitative and qualitative performance measures with a multilevel hierarchy. The empirical study of 11 Asia-Pacific international airports has demonstrated the effectiveness of the approach. The evaluation result would provide an airport with indicative information about its relative strengths and weaknesses in terms of performance measures associated with the airport operator, the passenger, and the airline. With its simplicity in concept and computation, the approach has general application in solving multiattribute evaluation problems involving both crisp assessments of quantitative attributes and fuzzy assessments of qualitative attributes.

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